Venus Surface Sample Return[1,2]

Robert Gershman, Erik Nilsen, Theodore Sweetser
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive - Mail Stop 301-170U
Pasadena, California 91109 USA
(818)354-5050
Robert.Gershman@jpl.nasa.gov
Erik.N.Nilsen@jpl.nasa.gov
Theodore.H.Sweetser-III@jpl.nasa.gov

Abstract—In cooperation with NASA's Solar System Exploration Subcommittee (SSES) the Jet Propulsion Laboratory (JPL) is conducting a series of studies to assess the feasibility of planetary science missions proposed for launch in the 2006-2010 time frame and to prioritize technology development steps that will enable these missions. Until recently the return of sample material from the surface of Venus was widely considered to be beyond the technological and financial capabilities of the NASA Space Science Program for this time frame, but technological and programmatic advances may now have brought such a mission within reach[1]. This paper describes the results of a study to investigate the feasibility of various options proposed for a Venus Surface Sample Return (VSSR) Mission and to develop a mission concept to be considered in NASA's strategic planning. Included will be discussions of the science objectives, the major system and subsystem trade-offs, and a preliminary mission concept.

TABLE OF CONTENTS

1. INTRODUCTION

The principal science objective of the Venus Surface Sample Return (VSSR) mission would be to return samples of surface and atmospheric material to Earth for detailed chemical analysis. Knowledge of the surface chemistry of Venus is based on limited observations done by the Venera landers[2][3]. We have no data on surface mineralogy and no idea of the volatile content of surface rocks. Understanding the surface material will help in calibrating models of the evolution of the atmosphere and the interior. Also, the venusian impact crater population is distributed randomly, preventing us from determining the ages of surface features.

Returning a sample of the venusian atmosphere is also of extremely high scientific priority. More detailed analyses of the atmospheric chemistry, in particular the isotopic composition, utilizing the more sophisticated laboratory equipment available on Earth would enable us to better address the nature and evolution of the venusian atmospheric greenhouse. In addition, we have little knowledge of the chemical composition of the lower atmosphere of Venus. The lower atmosphere is a key link between surface and interior processes; understanding the detailed composition of the lower atmosphere can help constrain the current reactions taking place between the surface and atmosphere, as well as address fundamental outstanding questions on the volcanic history of the planet.

Venus sample return missions have been proposed in the past[4], but a number of current developments have provided or will provide substantial additions to the technology base needed to assure success of such a proposal. In addition to the heritage provided by the Mariner, Venera and Vega missions of the 70s and 80s, a VSSR mission in the next decade will benefit from the understanding of the planet and particularly of aeroassist possibilities provided by Magellan, from the development of many elements of a planetary sample return mission by the NASA/CNES Mars Sample Return (MSR) Project (including ascent vehicle, orbiter, rendezvous and docking system and Earth entry vehicle), from extensive Venus balloon technology development work at JPL and elsewhere, and from the general trend toward smaller lighter spacecraft systems.

2. SCIENCE OBJECTIVES AND MEASUREMENTS

Characterization of the landing site, the sample and its environment through imaging and chemical analysis (both in situ on Venus and in the laboratory on Earth) are fundamental to the success of this mission.

[1] 0-7803-5846-5/00/$10.00

[2] Updated October 20, 1999

Science Objectives

Developing an understanding of how Venus evolved geologically will provide insight into the evolution of the Earth and facilitate understanding of the results of future searches for extra-solar Earth-like planets.

Objectives
1. Return a rock sample to Earth for analysis of age, composition, and origin.
2. Return samples of the Venus atmosphere to Earth for analysis of composition.
3. Document sample context.

Requirements
1. Return 100 g of bedrock material.
2. Document surface sample context by imaging and spectrometry during descent to meter scale resolution.
3. Return one atmospheric sample of 30 mg taken in lowest 20 km of atmosphere.
4. Measure atmosphere species during descent and on surface.

Measurement Objectives

Our knowledge of the surface chemistry of Venus is based on a limited number of elemental analyses done by the Venera landers. No data exists on surface mineralogy, which would provide significant constraints on models of evolution of the venusian crust. Similarly, the volatile content of Venus rocks is unknown. The amount of water contained in Venus surface samples will help constrain models of the evolution of the Venus atmosphere and interior. Even more importantly, the venusian impact crater population is distributed randomly, preventing determination of the ages of surface geologic units. Plains terrains cover most of the surface of Venus, but we have only a limited idea of their chemistry and little constraint on their age, which could range from recent to 750 million years. The chemistry of basalts associated with hotspot rises would provide important insights into the nature of the interior of Venus, while tessera terrains may be analogous to terrestrial ancient cratons.

Surface Targets:

- Plains
- Hotspot rises
- Tessera terrain

Measurement Strategy

Surface Sampling

Science objective - Obtain and store samples for return to the Earth for analysis.
- Drill mechanism for coring in bedrock
- core length of ~15- to 20-cm to obtain "pristine" sample; collect portion of bedrock that has not been altered through interaction with the atmosphere.
- Mechanism to deploy drill and deliver sample to return capsule

Instrument - Drill with device to store core.

Surface Imaging

Science objective - Evaluate the morphology and structure of the surface at scales of centimeters to meters—during descent and while on the surface; examine the processes by which surface rocks have been emplaced and modified (weathered); constrain general surface mineralogy.
- Descent imaging provides a regional to local context for returned samples, allowing them to be correlated to geologic units identified in Magellan radar data. Descent images of high resolution can be used to refine age relationships between volcanic units, characterize the degree of weathering and soil cover of the venusian plains, and determine the degree to which regional volcanic plains are made up of different volcanic flow units (single flooding event or built up over time from multiple flows).
- Spectral reflectance measurements to constrain oxidation state, Fe^{2+}/Fe^{3+} ratios.
- Determine if surface and atmosphere have the same oxidation state.
- Determine if magnetite or hematite is present on the surface.
- Degree of oxidation can help to put constraints on the surface age.
- Determine general mineralogy of crystalline rocks.
- Provide a means to determine if Magellan radar property information can be associated with multispectral properties.

Instruments - Active Pixel Sensor (APS) or Charge Coupled Device (CCD) camera with visible to Infrared (IR) filters (0.4 to 1.1 μm); eight filter positions.

Operations - Imaging during lander descent for navigation and site correlation with radar images; evaluation of the properties and characteristics of regional/local terrains; multispectral data to extrapolate information from surface sample.

Temperature and Pressure Sensing

Science objective - Accurate measurement of the near-surface and surface thermal properties is necessary for formulating models for likely mineral assemblages that are stable under current Venus conditions. Provides a means to test models to explain the presence of areas of high Fresnel reflectivity (low emissivity) observed in Magellan radar data.

Table 1: Instrument Subsystem Mass and Power

	Mass, kg	Power, W	
		Descent	Surface
Descent imager	0.2	1	
Multispectral imager	1		2
GCMS	2.5	15	15
Press., temp., accel.	0.2	1	1
Drill, VAV side	1.2		1
Drill, Lander side	10.4		150

Instruments - Net flux radiometer, thermocouple, pressure transducer

Operations - Measure temperature/pressure during descent to the surface and as part of surface operations.

Atmospheric Sampling

Science objective: Collect and store a sample of the Venus atmosphere from below 20 km for return to Earth for analysis. Measurement of elemental and isotopic abundances of noble gases (Xe, Kr, Ar, Ne) of Venus' atmosphere with sufficient precision will help to resolve between competing models of the origins of terrestrial atmospheres.

Characterization of the lowest scale height of the atmospheric will provide a basis for constructing and testing models for surface-atmosphere interaction.

Instrument - Device for collecting and storing 30mg (~1 ml) of atmospheric gasses

Operations - Extract sample of atmospheric gasses below 20 km altitude during descent to the Venus surface.

In situ Atmospheric Analysis

Science objective - Measure atmospheric constituents/species during descent below 20 km. In situ measurements will be compared with analyses performed on returned sample.

In situ determination of atmospheric species aids in testing and formulating models for surface-atmosphere interactions, provides a means to make comparisons with analyses of returned sample, and characterize any changes in the sample as a result of storage and transport at pressures and temperatures different from the ambient Venus environment.

Instrument - Gas-chromatograph mass spectrometer (GCMS).

Operations - Perform measurements below 20 km altitude to the surface.

The sample return container was estimated at 2 kg mass, including the "atmospheric sampler" option. Instrument mass and power requirements are summarized in Table 1.

3. Mission Design

The Earth-Venus leg uses a ballistic transfer with $C_3=10$ km^2/s^2, requiring about 4 months. The Venus approach hyperbola is targeted for a close flyby. As the spacecraft enters the atmosphere a ballute deploys and the spacecraft is aerocaptured into a "loose" (i.e., distant apoapsis) elliptical orbit about Venus. Shortly before apoapsis on this orbit, a plane-change maneuver places the spacecraft into an equatorial orbit to adjust periapsis for aerobraking. The equatorial orbit is required in order to reach landing sites of scientific interest.

Next, aerobraking reduces the apoapsis of the orbit. The small drag deceleration at periapsis gradually reduces apoapsis from 277,000 km to 300 km. Aerobraking takes about 230 days and is very sensitive to periapsis altitude, atmospheric density and ballistic coefficient. When an apoapsis of 300 km is reached, a small circularization maneuver raises periapsis to 300 km. The spacecraft is now in a 300-km, circular equatorial orbit. When the geometry with respect to the landing site is correct, the lander separates from the orbiter and fires a small rocket to deorbit. A ballute deploys as the lander enters the atmosphere. After the lander slows down, it releases the ballute and descends slowly to the surface in the dense atmosphere.

On the surface, the ultrasonic drill takes the core sample and transfers it to the Venus Ascent Vehicle. 1.5 hr after landing a balloon deploys and lifts the VAV to an altitude of 66 km. When the timing is correct, the first stage of the VAV fires. This is followed by two more solid rocket stages, which deliver the final small payload capsule to the 300-km orbit. The orbiter and the payload capsule rendezvous and the orbiter is ready to return to Earth. There are two options for the return leg: Option 1 uses a ballistic return from Venus to Earth, with Venus departure on 4 Dec. 2005 and Earth arrival on 9 May 2006, Option 2 uses a Solar Electric Propulsion (SEP) system for return in order to reduce propulsion system mass.

Table 2: Mission ΔV Budget in m/s

	Event	ΔV
Orbiter	Earth-Venus TCM	50
	Plane change to equatorial	120
	Aerobraking control	100
	Circularize 300-km orbit	50
	Orbiter Subtotal	320
Lander	Deorbit from 300-km orbit	120
VAV	Ascent (three-stage solid)	8380
Orbiter	Rendezvous with sample	225
Orbiter (Option 1)	Venus-Earth transfer	3410
	Venus-Earth TCM	20
Orbiter (Option 2)	Venus escape and Venus-Earth transfer requires 208 kg of xenon	9310

Venus departure is on 29 Sept. 2005 and Earth arrival on 29 May 2008. The long flight time for Option 2 is due to the spiral out from Venus to reach escape velocity. The hyperbolic approach speed at Earth is 4.1 km/s for Option 1 and 3.2 km/s for Option 2. The method of recovering the sample was not studied, but is assumed similar to the method used by the Stardust mission. The ΔV budget for the mission is shown Table 2.

Venus-Earth Leg (Ballistic)

The ballistic return to Earth (Option 1) departs Venus on 4 Dec. 2005. The hyperbolic excess velocity with respect to Venus is 3.05 km/s. The departure asymptote lies nearly in the Venus equatorial plane and is thus coplanar with the orbiter's 300-km orbit and no plane change ΔV is required at departure. The periapsis (300 km) velocity for the hyperbola is 10.56 km/s. The circular velocity of the orbiter is 7.15 km/s, so the departure ΔV is 3.41 km/s. This ΔV must be applied at a position in the orbit to get the correct Right Ascension (RA) of the asymptote. The spacecraft arrives at Earth on 9 June 2006 after a flight time of 187 days. The Earth approach hyperbolic velocity is 4.14 km/s.

Venus-Earth Leg (SEP)

The SEP return trajectory (Option 2) was studied in order to reduce Earth launch mass. There is a spiral out to escape from Venus followed by a heliocentric transfer to Earth. The spiral out from Venus starts on 29 Sept. 2005 and escape velocity is reached on 10 Dec. 2006, a duration of 437 days. The heliocentric phase lasts 536 days arriving at Earth on 29 May 2008. The total flight time is 973 days, considerably longer than the ballistic option. The initial wet mass of the spacecraft leaving Venus is 900 kg, which includes a dry mass of 692 kg and 208 kg of xenon propellant. The propulsion system uses one advanced SEP thruster and a 2.5 kW Gallium Arsenide (GaAs) solar array. The Earth-approach hyperbolic speed is 3.167 km/s.

Launch Vehicle Selection

For the ballistic return (Option 1), the study team obtained a total system mass of 4626 kg. The launch capability of the Delta IV M+(5,4) is estimated at 3500 kg for $C_3=10$ km^2/s^2. This gives a negative launch margin of −1126 kg. The possibility was investigated of improving launch vehicle performance by using a 4-m fairing rather than 5 m with four solid strap-ons, i.e. M+(4,4). However launch vehicle designers said that this configuration is not planned due to acoustic overpressure at launch. For the SEP return (Option 2), the study team obtained a total system mass of 3012 kg. With the same launch vehicle and C_3, this gives a positive margin of +488 kg. This is the baseline approach.

4. FLIGHT SYSTEM

The flight system consists of two major subsystems; the lander and the orbiter. The lander contains the landing structure, aeroentry ballute, sample collection and handling system, sample return canister, ascent balloon system and the ascent vehicle. The orbiter contains the orbiter structure, aerocapture ballute, sample tracking and capture subsystem, SEP system and the Earth entry vehicle. At launch, the combined vehicle mass is approximately 3000 kg and is sized to fit in the standard Delta class fairing. Table 3 provides a breakdown of subsystem mass and power use and Figure 1 illustrates one possible configuration.

Power

The power subsystem consists of several elements: The orbiter power subsystem, SEP subsystem, lander, ascent vehicle and sample canister. The orbiter power subsystem consists of a one meter GaAs articulating solar array providing 120 W of power and a 20 Ahr battery for energy storage. A separate solar array system is used for powering the SEP system and is kept in the stowed configuration until the SEP system is utilized for the return leg.

Table 3 – Spacecraft Mass and Power

	Mass (kg)	Power (W)
Total Lander Mass (wet)	**1826**	
Venus Ascent Vehicle	**476**	**320 (Burn)**
Stage 3 + Sample Total	42.5	1.8 (Burn)
Payload	2.0	
Stage 3		
Command and Data	0.1	0.1
Power	0.4	1.3
Propulsion (Star 13A)	4.95	
Structure	1.0	
Stage sep. system	0.3	
Cabling	0.1	
Thermal	0.01	
Mass/Power contingency	0.6	0.4
Propellant	33.2	
Stage 1 & 2	433.9	246.8
Attitude Control	22.2	212.5
Command and Data	0.1	2.0
Power	2.2	30.5
Propulsion	38.7	
Structure	18.3	
Launch Vehicle Adapter	2.6	
Cabling	3.3	
Thermal	0.01	
Mass/Power contingency	14.6	
Propellant	331.8	
Lander (wet)	**1350**	**300 (Drilling)**
Payload total	16.3	169.0
Instruments and Drilling Equipment	16.3	169.0
Lander Bus total (Dry)	1333.7	61.5
Attitude Control	0.8	8.8
Command & Data	1.1	7.6
Power	11.4	26.5
Propulsion (de-orbit)	8.5	
Inflation System	158.5	
Structure	160.1	
S/C Adapter	14.8	
Cabling	23.0	
Thermal	45.4	10 (descent)
Telecom	2.3	18.7
Mass/Power Contingency	127.8	69.2
Balloon (plus container)	94.6	
Propellant and Pressurant	143.5	
Ballutes (EDL Ballute and Aerocapture ballute)	541.9	
Orbiter (wet) – SEP	**1186**	106 (Orbiting)*
Payload total	20.0	
Earth Entry Vehicle	20.0	
Orbiter Bus total	1333.7	81.3*
Attitude Control	24.4	*
Command & Data	3.0	*
Power	52.0	*
Propulsion (bi-prop)	27.6	*
Propulsion (SEP)	73.6	*
Structure	183.0	
S/C Adapter	16.0	
Cabling	24.6	
Sample Capture Mech.	90.0	
Thermal	17.7	34.9
Telecom (high gain X-band)	10.9	46.4
Mass/Power Contingency	156.8	24.4*
Propellant and Pressurant (SEP and BiProp)	486.5	

(*) The power numbers do not include the SEP stage power of ~ 2.5kw, but are representative of the power needs in Venus orbit.

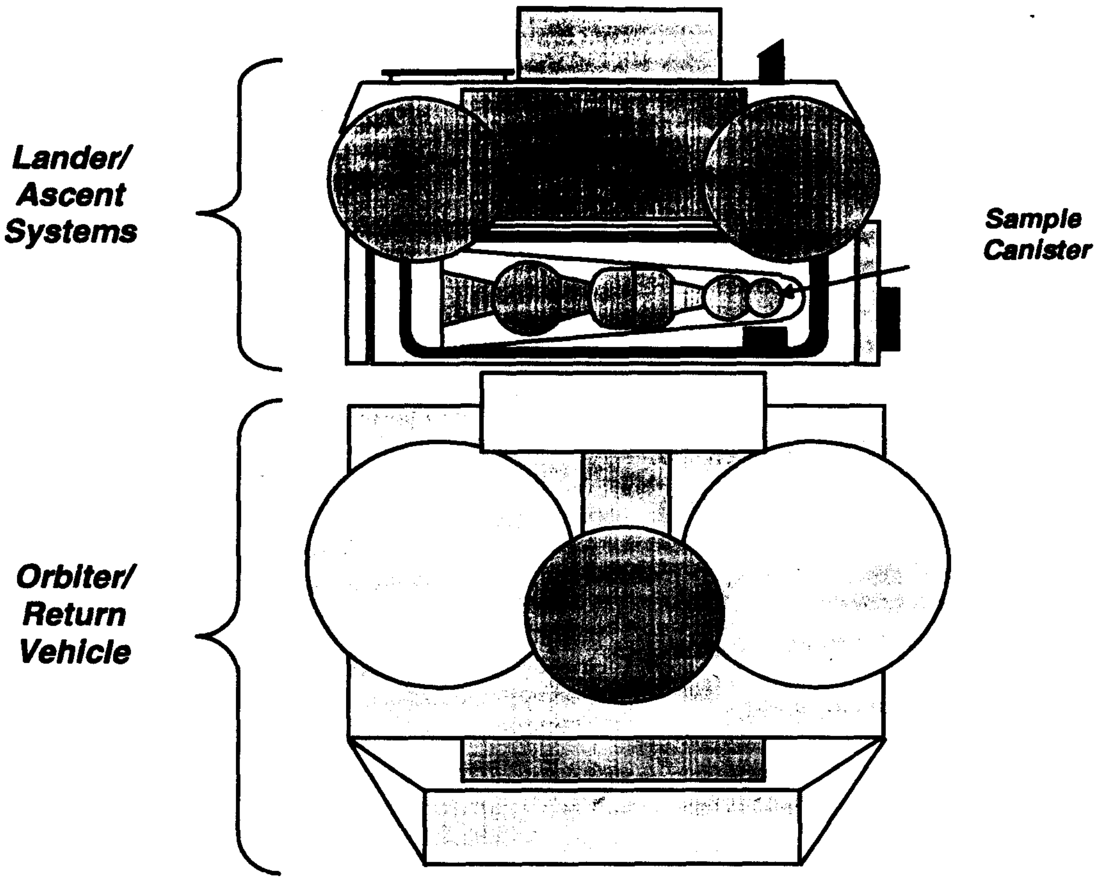

Figure 1 – Flight Systems Configuration

For the lander, ascent vehicle, and orbiting sample canister, batteries are used to provide the necessary power. For the sample canister, power is required for the radio tracking beacon.

Telecommunications

The telecommunications package provides communications capability from the Earth to the orbiter and from the orbiter to the lander. For Earth communications, a dual redundant X band system is used consisting of two Small Deep Space Transponders (SDST), solid state power supplies and low gain omnidirectional antennas. The link provides 40 bps capability at Venus.

The lander to orbiter communication is used to transmit the science information and images of the landing site for storage on the orbiter. This bidirectional link consists of a one watt UHF transmitter and a 32 inch patch antenna, providing 128 kbps capability. It is also used during the ascent phase.

Avionics

The avionics system uses X2000 delivery 1 technology to provide processing, control and storage functions on the orbiter and the lander. Sizing of the storage and processing is to be determined based upon the science requirements, however, the orbiter must provide capability to store all science and critical engineering data during the lander operations.

Attitude Control

The ACS system has elements on each of the major subsystems. For the orbiter, the ACS provides 3 axis control with a sensor system consisting of star tracker, sun sensor and Inertial Reference Units (IRUs). For the ballute subsystems for aerocapture and aeroentry, accelerometers are used for closed loop control of the aeroassist process. For the ascent vehicle, an IRU and Thrust Vector Control (TVC) system is provided for three axis control of the first two stages. If active hazard avoidance is employed, IRUs will be provided on the lander for control.

Propulsion

The propulsion subsystem has several elements. For trajectory corrections, orbit maneuvers and sample rendezvous, the orbiter is equipped with a bipropellant chemical propulsion system using a single 470 N main engine. Four 22 N and twelve 0.9 N hydrazine thrusters are provided for thrust vector control. For the return leg, the SEP system is based upon a single advanced NSTAR thruster using 208 kg of Xenon propellant and associated hardware.

The ascent vehicle is a three stage solid propellant vehicle with active thrust vector control and a second stage cold gas thruster based Reaction Control System (RCS). The first stage is based on a Star 24C motor and has 227 kg of propellant (Isp=283 s), providing 1850 m/s delta-V. The second stage is based upon a Star 17A motor and has 95 kg of propellant (Isp=287 s) providing 2073 m/s delta-V. The third stage is equivalent to the Star 13A motor, with 33 kg of propellant at an Isp of 287 s and provides 4455 m/s. Total delta-V provided is 8378 m/s.

Thermal Subsystem

The thermal subsystem provides thermal control for all elements of the flight system. For the orbiter, relatively standard thermal protection is provided consisting of Multi Layer Insulation (MLI) and passive cooling using louvers. Additional thermal protection may be required in certain areas to protect the orbiter and lander during aerocapture, and the lander during aeroentry.

For the landed operations a passive thermal system is used to control the rate of heating of critical components. The system is designed to use thermal capacitance to provide up to 1.5 hours of surface operations. The insulation consists of a semi-permeable blanket that envelops the critical components. There is some concern that CO_2 liquefaction at these pressures and temperatures could cause problems, so an alternative has been proposed to have a sealed system with a pressurant gas used to insulate and keep CO_2 out of the system. Pressure vessel implementations were examined and discarded due to the excessive weight and implementation issues.

For the Earth entry vehicle, an aeroshell and passive thermal control system will control the heating during entry.

5. COST

End-to-end cost estimates for all of the VSSR concepts studied were in the $500-600M range (in FY 1999 dollars, including launch vehicle and operations).

6. TECHNOLOGY

Several technology developments are essential to the success of this mission. Because of the critical nature of these technologies and the uniqueness of the Venusian environment, a precursor technology validation mission is suggested, although not included in the cost estimates above.

Ballutes

The aerocapture ballute for this mission will be very large (greater than 30 m in diameter), and technology must be developed for storage, deployment, and release. The descent ballute will require development of materials tolerant of the high temperatures and acid content of the lower atmosphere.

High-Temperature Ascent Balloon

A balloon that can be inflated at the temperature on the surface of Venus (700 K) is required for this mission. Without this, there is no efficient way to return a sample.

VAV Guidance & Control

The 3-stage solid rocket VAV concept is a logical follow-on to ascent vehicle concepts being developed for Mars, but launch from a balloon introduces a new suite of guidance and control challenges that will require technology development.

Thermal Control for VAV & Lander

Thermal control concepts must be developed that will provide protection for the VAV and all landed elements during descent, surface operations, balloon lift to 66 km, and launch. The concepts must be compatible with required imaging and sample collection activities.

7. CONCLUSIONS

Being the most earth-like of the terrestrial planets in terms of size, mass, and location in the solar system, understanding the geologic evolution of Venus will provide key insights into how the Earth has evolved. Returning a sample from the surface of Venus is a technically challenging task. Using a highly constrained VAV, a system of balloons and ballutes appears to make the return of a sample from the Venus surface feasible. Use of an SEP stage to return to Earth provides benefits in terms of both mass and cost. In order to avoid many of the thermal constraints to operating in the harsh Venus environment, the mission studied here is designed to spend a minimum amount of time on the surface. Sample context is very important for a mission such as this. The ability to image the sample in situ, before and after extraction is included. The numerous unique elements combine to make this a relatively expensive mission.

8. ACKNOWLEDGMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors wish to acknowledge the efforts and contributions of the members of the Venus Surface Sample Return Study team led by David Rodgers, and the Jet Propulsion Laboratory Team X study team, led by Robert Oberto.

References

[1] White House National Science and Technology Council *National Space Policy – Fact Sheet*, National Science and Technology Council (NSTC) Presidential Decision Directive (PDD), 1996

[2] D. M. Hunten, L. Colin, T. M. Donahue, V. I. Moroz ed., *Venus*, University of Arizona Press, 1983

[3] S. W. Bougher, D. M. Hunten, R. J. Phillips ed., *Venus II*, University of Arizona Press, 1997

[4]. Coradini, M et al, *Venus Sample Return Assessment Study Report*, ESA Document SCI(98)3, 1998

***Robert Gershman** is Manager, Deep Space Mission Studies/Advanced Technology at JPL, responsible for mission concept studies and technology planning for NASA's Solar System Exploration theme. Previous JPL assignments have included Deputy Manager of the Galileo Science and Mission Design Office and Supervisor of the Mission Engineering Group. Before coming to JPL, he was a Senior Research Engineer at Ultrasystems, Inc. and a Group Engineer in the Propulsion Department at McDonnell Douglas Astronautics Co. He has a BS from Caltech and an MS from UCLA.*

***Erik Nilsen** is a mission and flight systems engineer in the Flight Systems Engineering section at the Jet Propulsion Laboratory. He was the Flight Systems engineer for the Venus Surface Sample Return mission study and is a member of the staff of the Program Architecture and Systems Engineering Office. He is currently active in advanced concepts development for In Situ exploration and in technology development for advanced robotic exploration. Former positions included Integration and Test Architect for the X2000 technology development project and Deputy flight systems manager for the Galileo Orbiter Engineering Team. He has a BSEE from Texas A&M University and an MSEE from University of Southern California.*

***Ted Sweetser** is a mathematician who works as an astrodynamicist and mission architect at the Jet Propulsion Laboratory. He has been active in both designing missions for NASA and developing software tools for that; currently he is concentrating primarily on design of future missions. He has a B.A. from Boston College and an M.A. and Ph.D. from the University of California, San Diego.*